Recent progress in development of APC Nb_3Sn conductors

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ASC 24 SALT LAKE CITY
SEPTEMBER 1 – 6
SALT PALACE CONVENTION CENTER

Motivations

Better Nb_3Sn conductors are still needed for FCC-hh.

Ballarino, Bottura, *IEEE TAS*, 25, 6000906 (2015)

TABLE I

TARGETS FOR FUTURE R&D ON Nb_3Sn FOR HEP APPLICATIONS

Strand diameter	(mm)	0.5 … 1
Non-Cu J_C (16 T, 4.2 K)	(A/mm^2)	≥ 1500
$\mu_0 \Delta M$ (1 T, 4.2 K)	(mT)	≤ 150
$\sigma(\mu_0 \Delta M)$ (1 T, 4.2 K)	(%)	≤ 4.5
D_{eff}	(μm)	≤ 20
RRR	(-)	≥ 150
Unit Length	(km)	≥ 5

If the target field is changed to 14 T, these parameters are still relevant.

- **J_c spec can be relaxed, but higher J_c is still desired to reduce coil size & cost.**
  - **A big consideration for a real collider**
  - **May allow operation at 4.5 K for higher efficiency**

- ***M* of RRP is large and needs to be reduced, as large *M* leads to field errors, flux jumps, a.c. loss.**
  - **$M \propto J_c * d_{eff}$. d_{eff} = 1.2-1.3*d_{sub} for RRP, & ≈ d_{fila} for PIT**
  - **For RRP wires, $d_{eff} \leq 20$ μm means $d_{sub} \leq 16$ μm, not likely achievable**

Coil geometry		Cos-theta	Block	Common Coil
Deff	μm	50	50	50
Xi	--	1	1	1
I1	Inom (50 TeV)	11060	10465	16100
I2	Ireset	100	100	100
I3	Iinj (3.3 TeV)	729.96	690.69	1062.6
I4	Inom (50 TeV)	11060	10465	16100
AC-loss (2 Ap)	J/m	18330	19603	23489
AC-loss/Asc	J/m$_3$	4728455	4633384	4776274

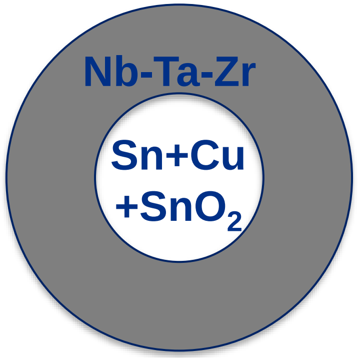
The AC loss is twice the target. LHC is 0.5 kJ/m.

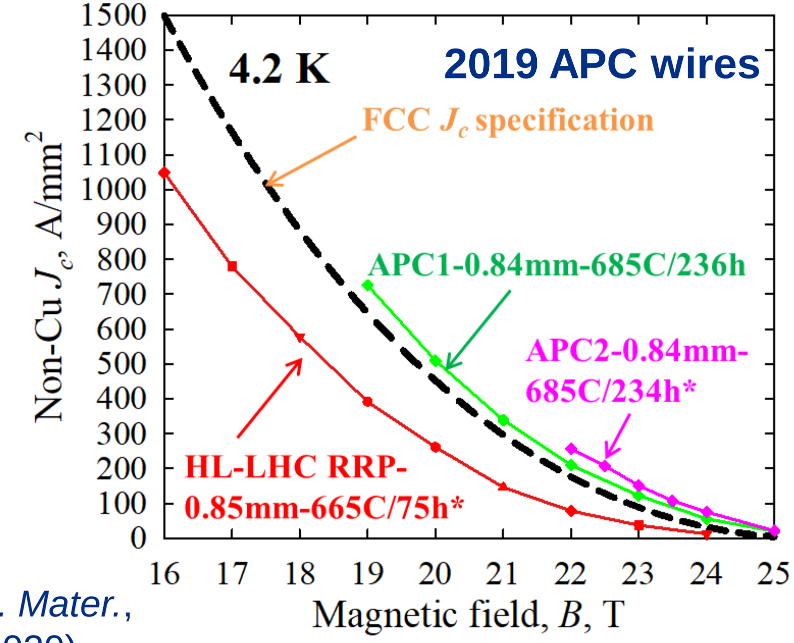
S. Izquierdo Bermudez, https://indico.cern.ch/event/679654/

Brief review

- 2014: internal oxidation first demonstrated in Nb_3Sn wires, showing refined grain size & higher J_c.
  - X. Xu, M. Sumption, X. Peng, E. Collings, *Appl. Phys. Lett. 104*, 082602 (2014).
- 2015-2017: binary PIT wires were developed at SupraMagnetics and Hyper Tech. Low B_{irr}.
- 2018: began to develop Ta-doped APC PIT wires using Nb-4%Ta-1%Zr alloy tubes.
- 2019: non-Cu J_c first reached FCC specification.
  - But poor wire quality, low RRR, instability issue. This has held us back from scaling up APC wire production.
- Since 2020: optimization of wire design and fabrication, to improve wire quality and solve the instability issue.

APC filament design: (same design w/ standard PIT, only different raw materials)



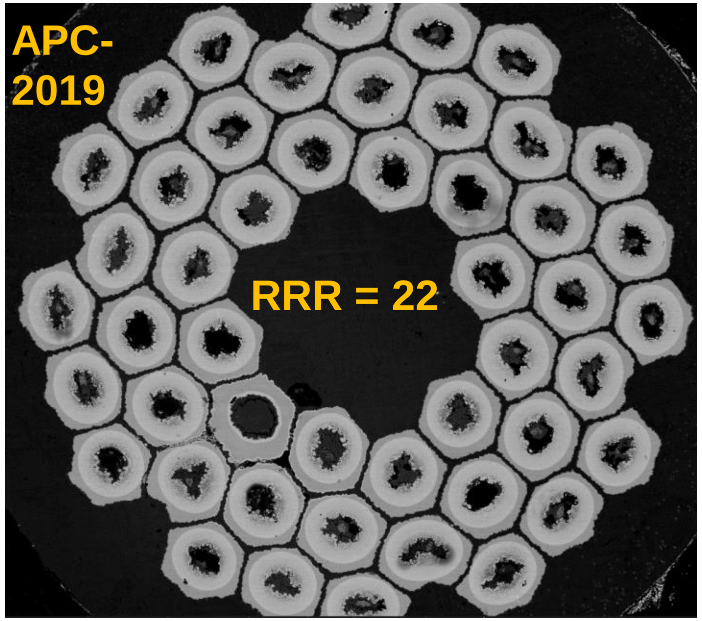


X. Xu et al., *Scr. Mater.*, 186, 317-320 (2020)

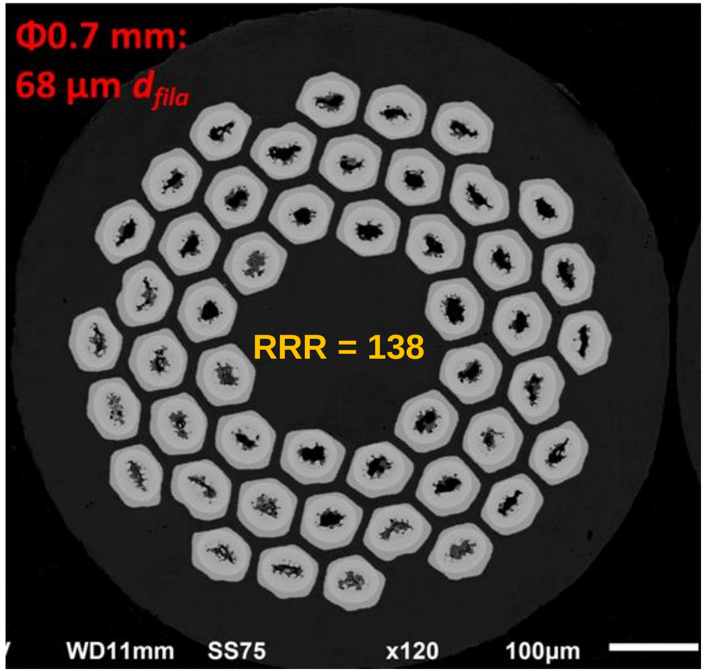
Solving the wire quality and instability issue

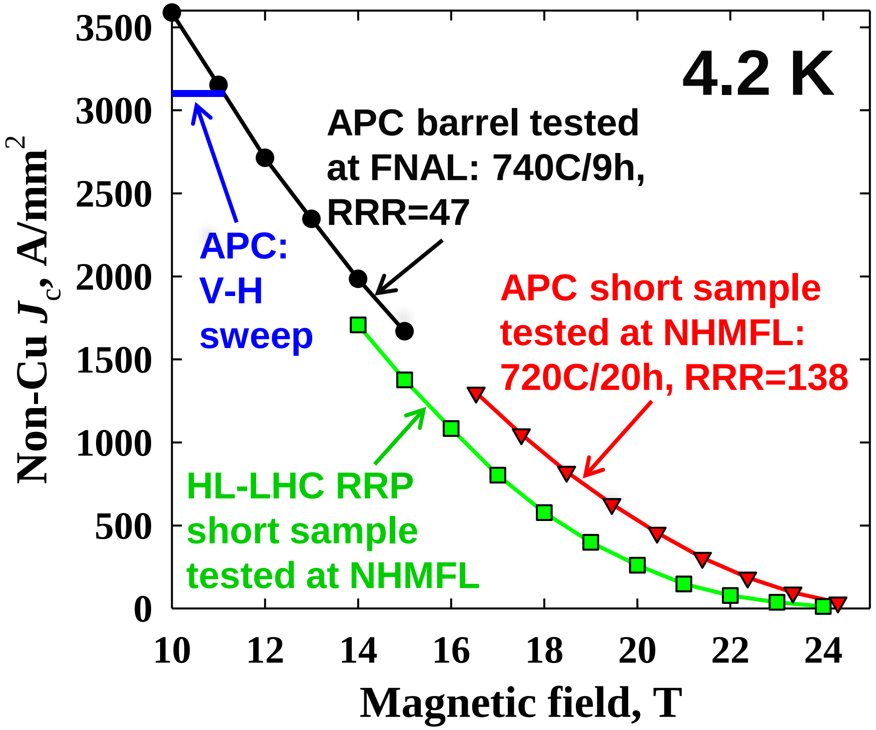
- What has been done:
  - Optimize wire design. The 2019 wires had very aggressive design, causing poor wire quality.
  - Use Nb alloy tubes with higher quality. Previous tubes had quality issue. New ATI tubes are better.

2019 wire: aggressive recipe + old Nb alloy tube w/ low quality:



Recent wire, using ATI Nb-Ta-Hf:





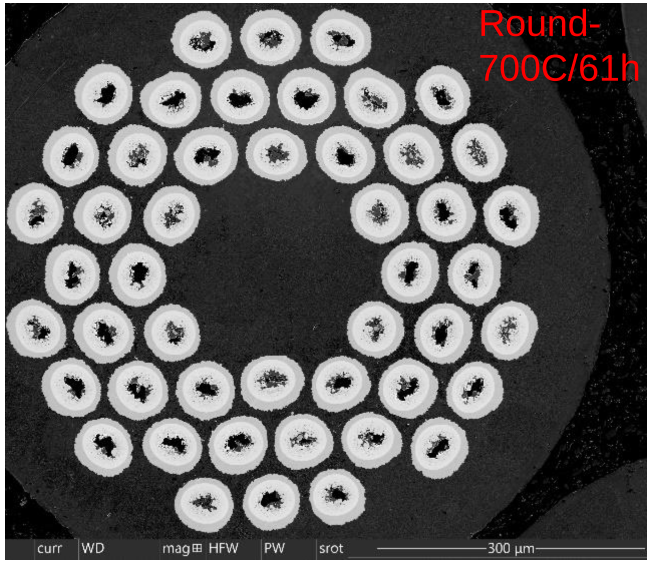
APC wires made using Nb-Ta-Hf seem to have lower $F_{p,max}$ and thus J_c than those using Nb-Ta-Zr.

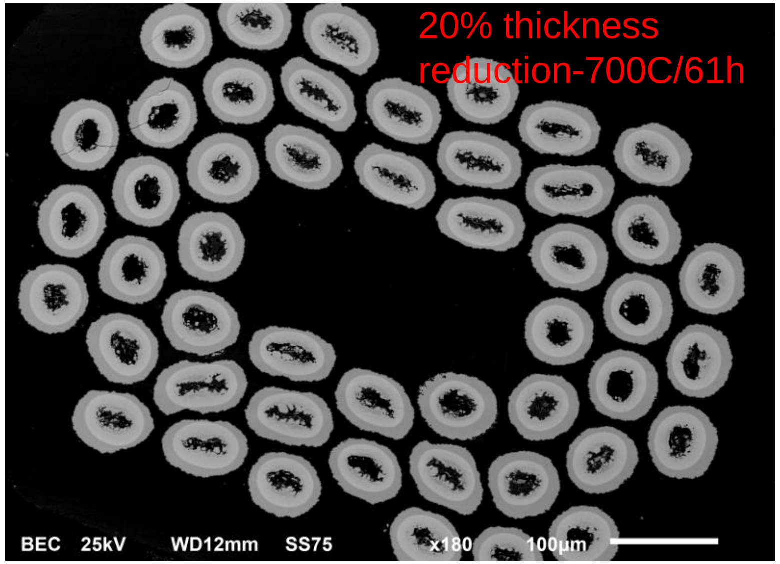
- Stability can be further improved by (1) optimizing heat treatment to increase RRR, (2) reducing filament size.
- Some instability was due to testing in the short sample form

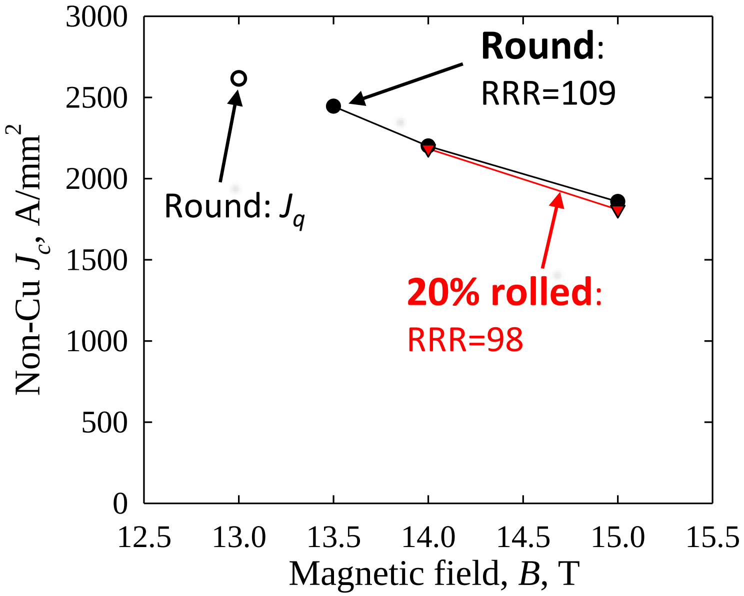
Other developments

1. Studied how to optimize wire design to reduce rolling degradation:

(1) Increase filament spacing, (2) change filament shape from hexagonal to round.





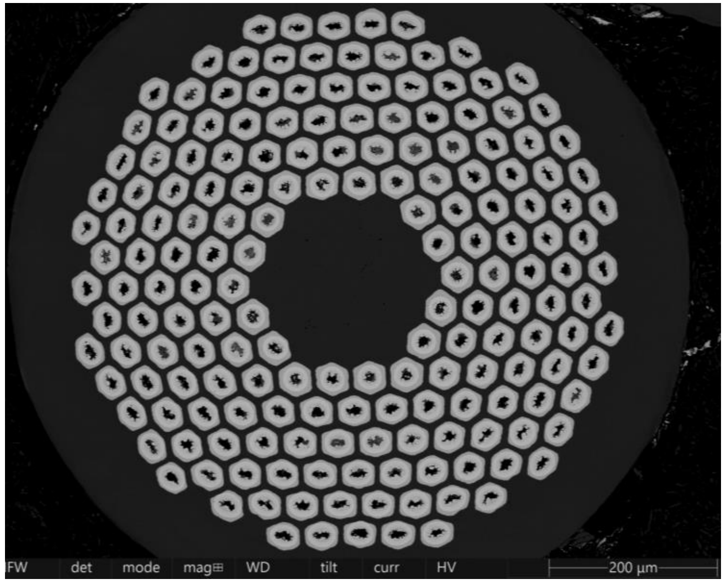


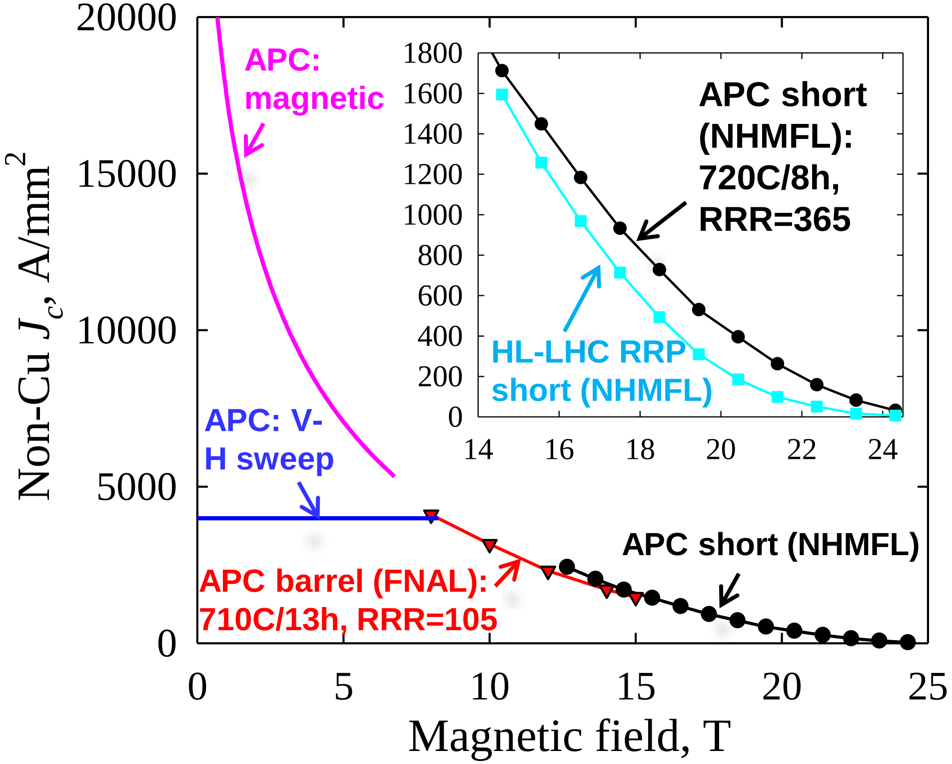
- **Little decrease in J_c.**
- **Only a small decrease in RRR.**

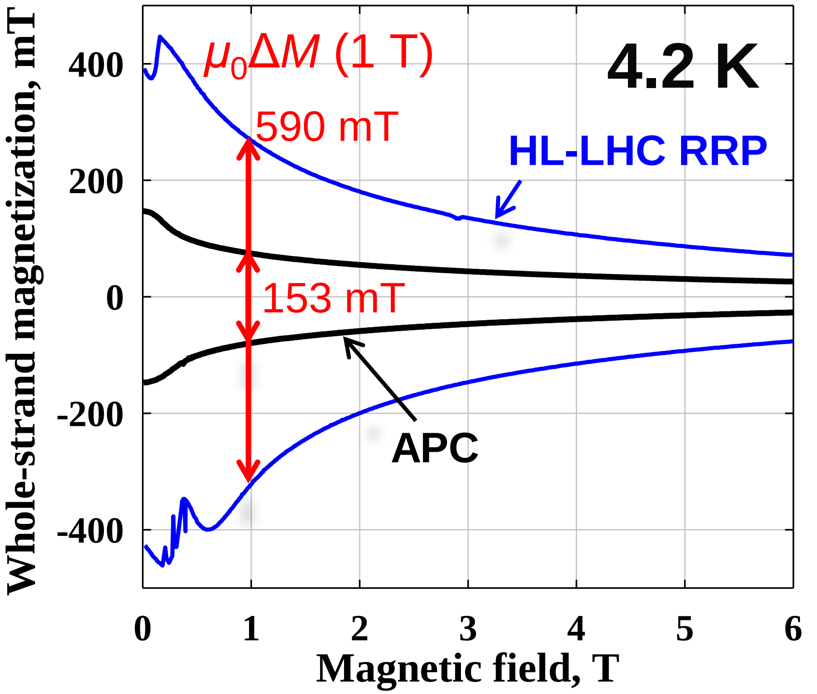
2. Development of 180/217-stack wires with small filament size. See next slide.

APC wires with small filament size

APC: still using ATI Nb-Ta-Hf, Φ0.8 mm, 38 μm d_{fila}





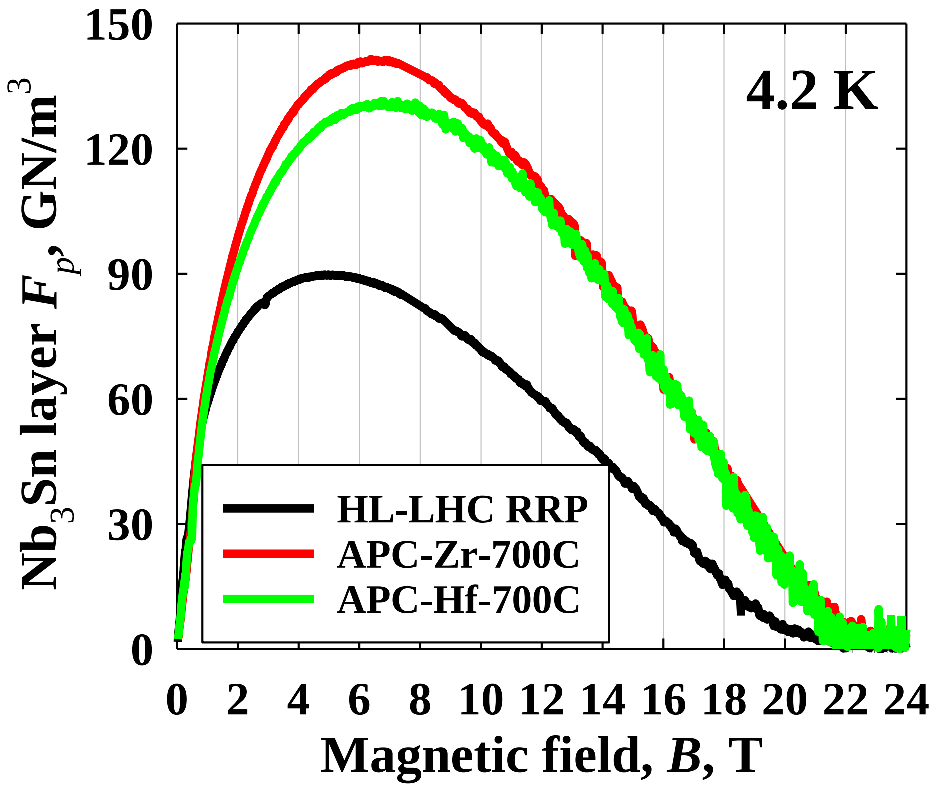


- The $\mu_0 \Delta M$(1 T) of this APC wire is only 1/4 of RRP, and almost meets the $\mu_0 \Delta M$(1 T) specification (≤150 mT).
- Compared w/ the RRP, the APC wire reduces AC loss by 70%. Greatly reduces heat load for FCC cryoplants
- The APC wire, despite higher J_c above 14 T, has much lower M than the RRP wire due to two reasons:
  - Although d_{sub} of RRP is not much larger than APC (55 vs 38 μm), d_{eff} of RRP is much larger (70 vs 40 μm).
  - APC effect: J_c-B curves of APC wires are much flatter. With same J_c(15 T), APC has lower J_c(1 T). See next.

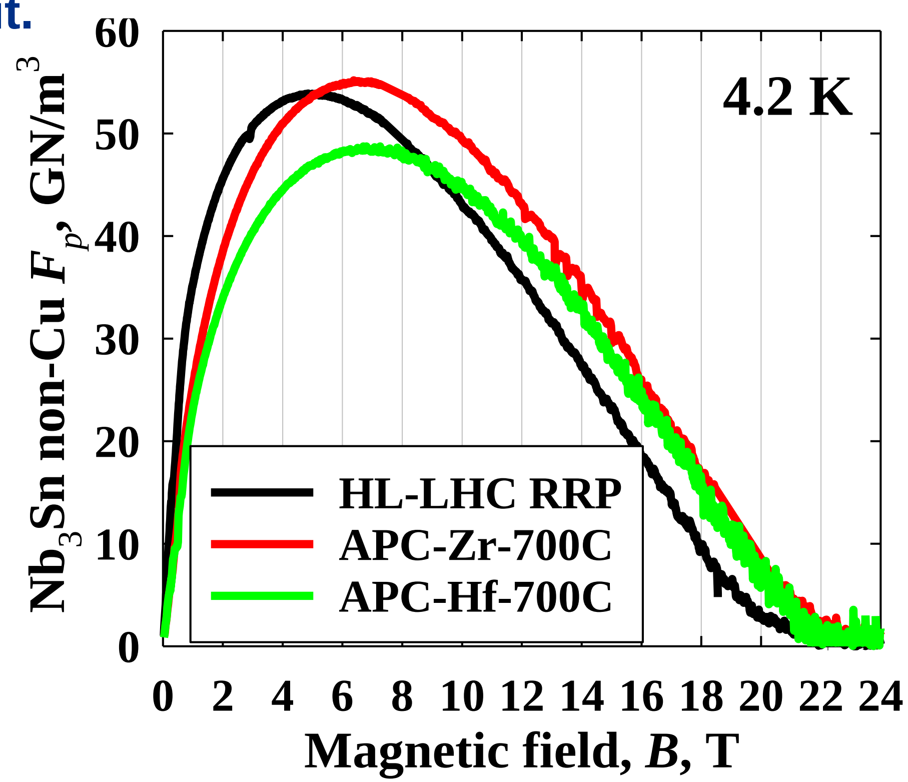
How does internal oxidation influence J_c?

- In the early days of APC wires, we believed that APC increases J_c due to refined grain size & higher $F_{p,max}$.
- But studies in recent years cast doubt on it.

Measured in a VSM up to 25 T at NHMFL:



- APC indeed has higher layer $F_{p,max}$.
- $F_{p,max}$ of APC-Zr is ~10% above APC-Hf.



- Non-Cu $F_{p,max}$ of APC wires is not higher than RRP.
- This is because RRP has higher Nb_3Sn fraction in subelements than APC (60% vs 30-40%).

Xu et al, Supercond. Sci. Technol. 36 085008 (2023)

- With similar non-Cu $F_{p,max}$, what really causes the J_c change is the F_p-B curve peak shift.
- Influence of APC on non-Cu J_c is field dependent: APC wires have higher J_c only at high field, but have lower J_c at low field.

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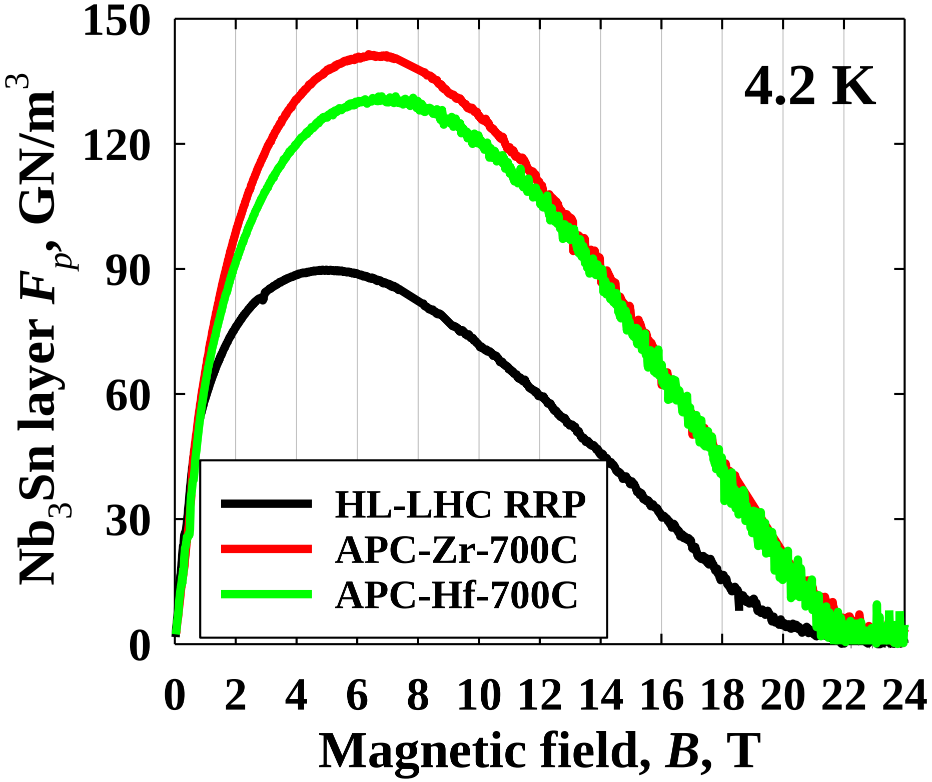

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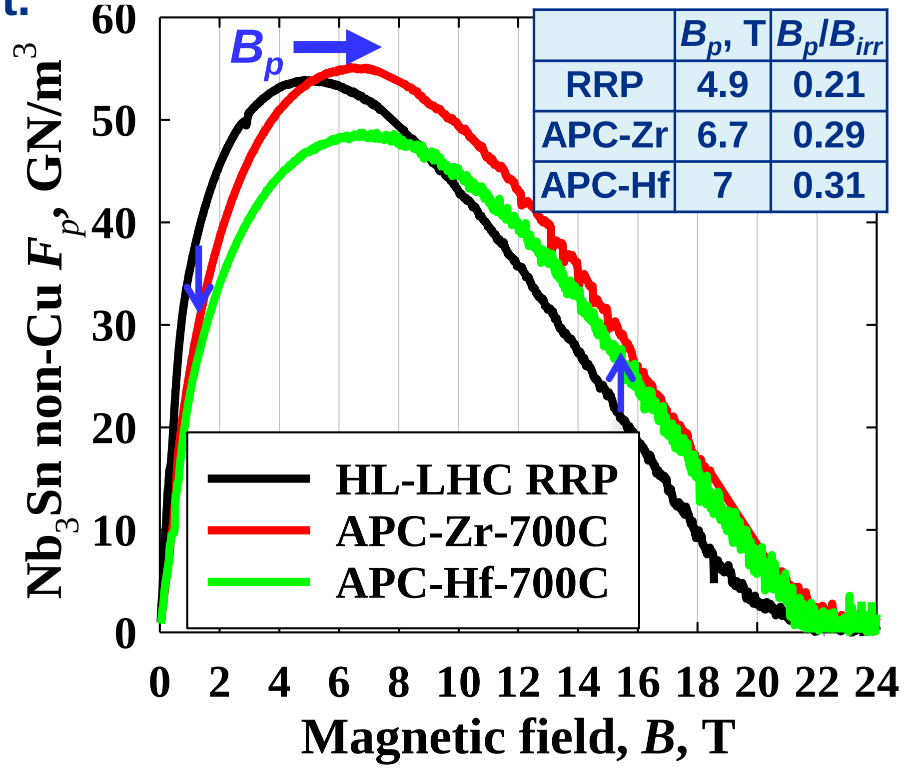

	B_p, T	B_p/B_{irr}
RRP	4.9	0.21
APC-Zr	6.7	0.29
APC-Hf	7	0.31

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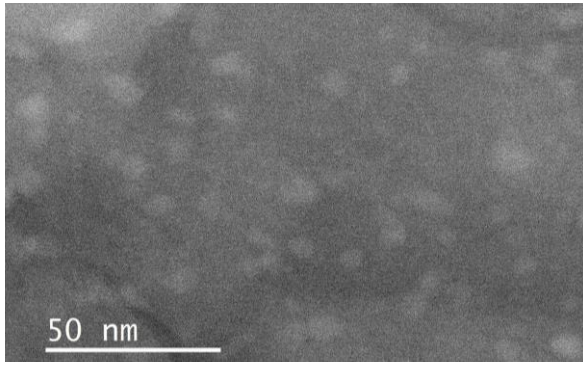
What determines F_p-B curve peak shift in APC wires?

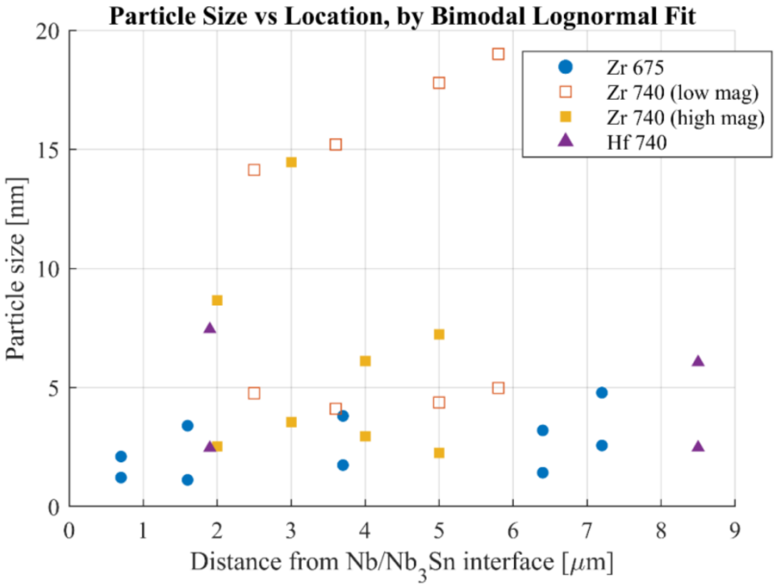
I. $Zr(Hf)O_2$ particles: size and distribution

- Nb_3Sn flux line core diameter: 2ξ ≈ 7 nm (4.2 K).
- Oxide particle size: mostly 1-15 nm, suitable as point pinning centers.

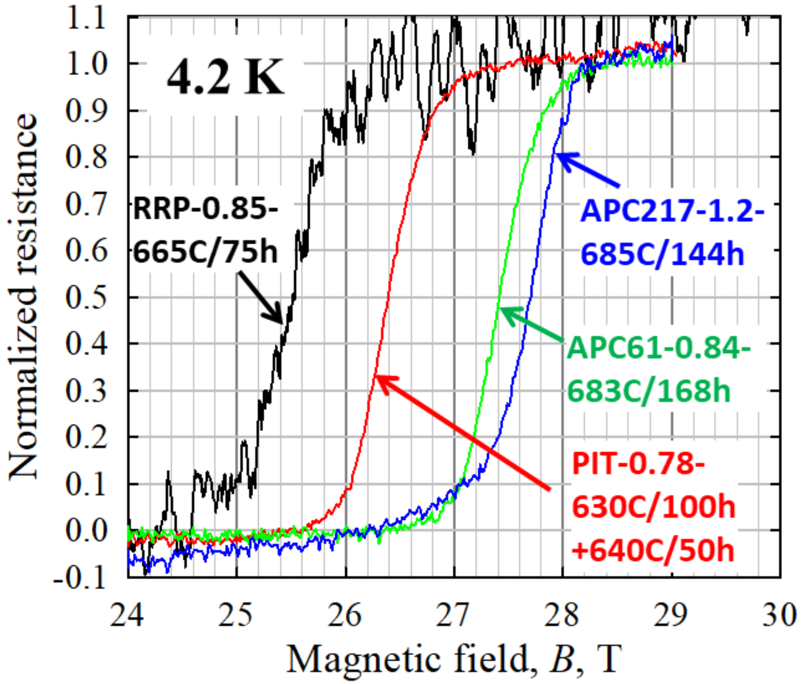


- GB pinning: $F_P = C_0 b^{0.5}(1-b)^2$. F_P-B curves peak at $0.2B_{irr}$.
- Point pinning: $F_P = C_0 b(1-b)^2$. F_P-B curves peak at $1/3B_{irr}$.
- APC wires: have both. Smaller particles + denser ➔ higher point pinning %.

- Data from J. Rochester PhD dissertation:
- Lower HT temperature ➔ smaller particle size.
- HfO_2 particles tend to be smaller than ZrO_2.



II. APC wires have higher B_{irr} & B_{c2} (1 T higher than non-APC PIT, ~2 T above RRP).



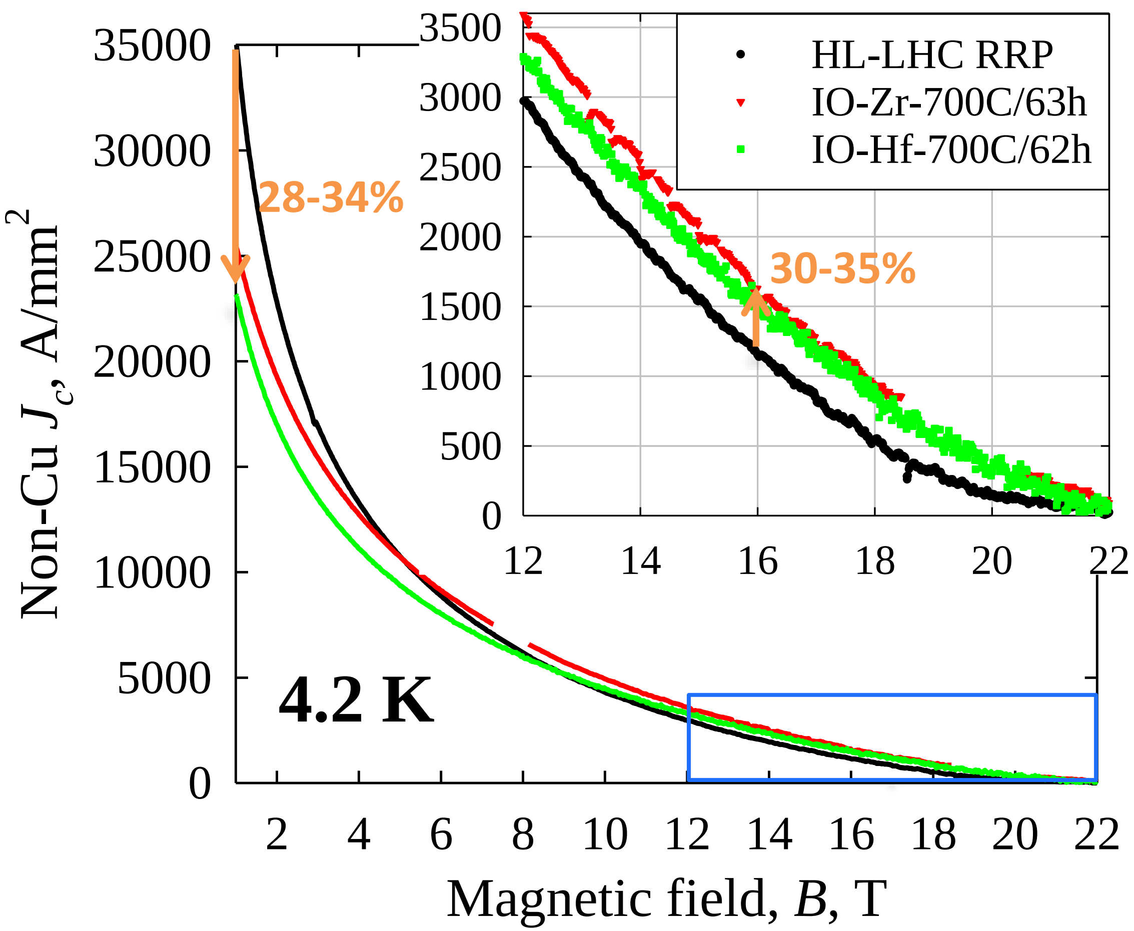
Xu et al., *J. Alloys Compd.* 845 (2020) 156182

Similar results were reported by U. Geneva.

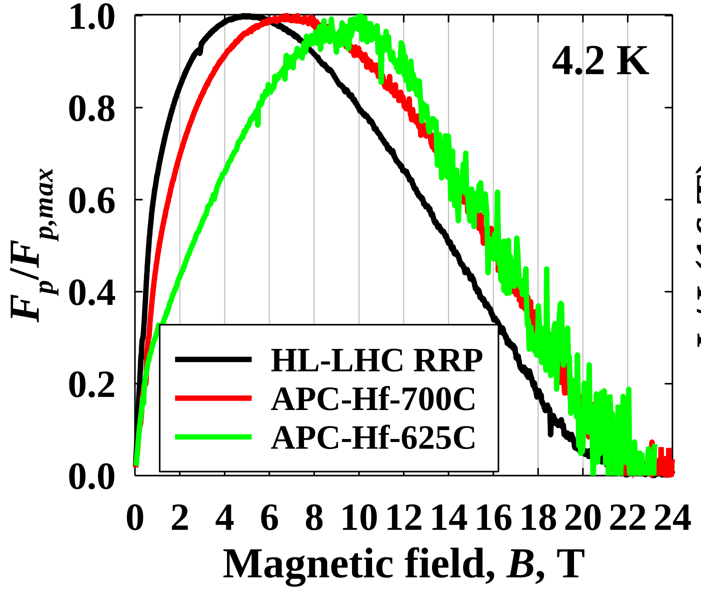
F. Buta et al., J. Phys. Mater. **4** 025003 (2021)

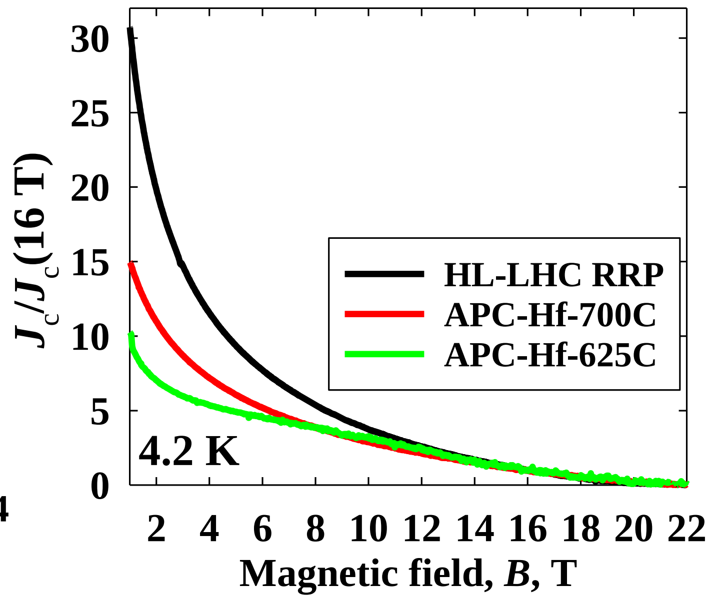
- We found that internal oxidation increases Sn content of Nb_3Sn (24-25 at.%).
- This may be the cause of higher B_{irr} & B_{c2}.

Quantitatively, how much does the F_p-B curve peak shift influence J_c?



The effect is stronger for APC wires w/ lower HT temperature, because particles are smaller & denser.





APC-Hf-625C: F_p-B curve peaks at 10T, near 0.5$_{Birr}$. It is over point pinning. Maybe individual pinning? J_c-B is almost linear

	HL-LHC RRP	ZrO_2-700C	HfO_2-700C	HfO_2-625C
J_c(1 T)/J_c(16 T)	31	15.6	15	10.3

W/ same J_c(16T), the J_c(1T) of APC is 1/3-1/2 of RRP, thus lower M(1T)

J_c-B curves of APC are flatter than RRP.

Field	1 T	6 T	12T	16T	18T
J_c(APC-Hf)/J_c(RRP)	0.66	0.9	1.1	1.32	1.67

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Ongoing work and next steps

- **Changes in technicians at HyperTech and sources of raw materials recently have led to some wire quality issues. This has caused some delay. We are working to solve this problem.**

- **Lower HT temperature is desired but may influence formation of coarse-grain and fine-grain Nb_3Sn, thus J_c. We are working to understand this. See Fang Wan's talk later.**

- **APC wires based on Nb-Ta-Zr seem to have higher $F_{p,max}$ and higher J_c than those using Nb-Ta-Hf. Next, fabrication of APC wires using Nb-Ta-Zr tubes from ATI.**

- **Electro-mechanical tests of APC wires: axial tensile, transverse pressure, etc..**

- **Now that instability is less of a concern, we are starting preparation for making long wires.**

Summary

- **RRP and standard PIT wires are already good conductors. What is the core value of APC wires?**
  - **Enhance "good J_c" (i.e., high-field J_c, ≥12-16 T). This is the useful J_c for high-field magnets.**
  - **Reduce "bad J_c" (i.e., low-field J_c, <5T). It is high but not useful; causes high *M* & related issues (e.g., dominates the AC loss).**
  - **APC does this by flattening the J_c-*B* curve (a result of F_p-*B* curve peak shift).**
- **The APC wire made recently with 38 μm filament size has *M*(1 T) that is 1/4 of HL-LHC RRP. This reduces the hysteresis loss by ~70%.**
- **Wire quality and stability of APC wires has been significantly improved due to improved wire design & use of better tubes. Stability issue is not a big concern anymore (4.2 K).**
- **Now preparing for making big billets.**

Acknowledgement

This work is supported by an Early Career Award from US Department of Energy.

Some tests were done at NHMFL, which is supported by National Science Foundation Cooperative Agreement No. DMR-1644779 and State of Florida.

Thanks to Eun Sang Choi, Jan Jaroszynski and Griffin Bradford for the helps in the tests.

Thank you for your attention!